SCATTEROMETRY FOR SAMPLES WITH NON-UNIFORM EDGES

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PRIORITY CLAIM

The present application claims priority to U.S. Provisional Patent Application Serial No. 60/459,046, filed March 31, 2003, the disclosure of which is incorporated in this document by reference.

TECHNICAL FIELD

The present invention relates generally to optical methods for inspecting and analyzing semiconductor wafers and other samples. In particular, the present invention relates to the use of scatterometry to analyze samples that have non-uniform edges.

BACKGROUND OF THE INVENTION

As semiconductor geometries continue to shrink, manufacturers have increasingly turned to optical techniques to perform non-destructive inspection and analysis of semiconductor wafers. Techniques of this type, known generally as optical metrology, operate by illuminating a sample with an incident field (typically referred to as a probe beam) and then detecting and analyzing the reflected energy. Ellipsometry and reflectometry are two examples of commonly used optical techniques. For the specific case of ellipsometry, changes in the polarization state of the probe beam are analyzed. Reflectometry is similar, except that changes in intensity are analyzed. Ellipsometry and reflectometry are effective methods for measuring a wide range of attributes including information about thickness, crystallinity, composition and refractive index. The structural details of various metrology devices are more fully described in U.S. Patent Nos. 5,910,842 and 5,798,837 both of which are incorporated in this document by reference.

As shown in Figure 1, a typical ellipsometer or reflectometer includes an illumination source that creates a mono or polychromatic probe beam. The probe beam is focused by one or more lenses to create an illumination spot on the surface of the sample under test. A second lens (or lenses) images the illumination spot (or a portion of the illumination spot) to

a detector. The detector captures (or otherwise processes) the received image. A processor analyzes the data collected by the detector.

Scatterometry is a specific type of optical metrology that is used when the structural geometry of a sample creates diffraction (optical scattering) of the incoming probe beam. Scatterometry systems analyze diffraction to deduce details of the structures that cause the diffraction to occur. Various optical techniques have been used to perform optical scatterometry. These include broadband spectroscopy (U.S. Patent Nos. 5,607,800; 5,867,276 and 5,963,329), spectral ellipsometry (U.S. Patent No. 5,739,909) single-wavelength optical scattering (U.S. Patent No. 5,889,593), and spectral and single-wavelength beam profile reflectance and beam profile ellipsometry (U.S. Patent No. 6,429,943). Scatterometry in these cases generally refers to optical responses in the form of diffraction orders produced by periodic structures, that is, gratings on the wafer. In addition, it may be possible to employ any of these measurement technologies, e.g., single-wavelength laser BPR or BPE, to obtain critical dimension (CD) measurements on non-periodic structures, such as isolated lines or isolated vias and mesas. The above cited patents and patent applications, along with PCT Application WO 03/009063, U.S. Application 2002/0158193, U.S. Application 2003/0147086, U.S. Application 2001/0051856 Al, PCT Application WO 01/55669 and PCT Application WO 01/97280 are all incorporated herein by reference.

To analyze diffraction, scatterometry systems use a modeling process. The modeling process is based on a parametric model of the particular sample being analyzed. The model is evaluated to predict the empirical measurements that a scatterometer will record for the sample. The predicted measurements and the empirical measurements are compared to determine if the model matches the empirical results. The model is then perturbed and re-evaluated until the predicted results and empirical results match within a desired goodness of fit. At that point, the parametric model is assumed to match the sample being analyzed.

As shown in Figure 2, a typical scatterometry sample includes a scattering structure formed on a substrate. For the specific example of Figure 2, the scattering structure is a grating composed of a series of individual lines. In general, the scattering structure may be periodic (as in the case of Figure 2) or isolated. Isolated structures include, for example, individual lines or individual vias. The scattering structure of Figure 2 is uniform (i.e.,

exhibits translational symmetry) along the Y axis. For this reason, this particular scattering structure is considered to be two-dimensional. Three dimensional scattering structures are also possible both in isolation (e.g., single via) or periodically (e.g., pattern of vias). The scatting structure is covered by an incident medium that is typically air but may be vacuum, gas, liquid, or solid (such as an overlaying layer or layers). One or more layers may be positioned between the scattering structure and the substrate. During analysis, a probe beam is directed at the scattering structure. For most applications, the probe beam intersects the scattering structure at a normal angle—it is perpendicular to the lines from which the scattering structure is formed. It is also possible to use a non-normal angle. This is referred to as conical scattering.

In practice, it is not generally possible to construct semiconductor wafers with the degree of orthogonality shown in Figure 2. This is due to a number of physical limitations, such as the accuracy of the equipment used during fabrication. The overall result is that the scattering structures typically included in semiconductor wafers tend to have sloping instead of vertical walls, rounded corners at the foot and top of lines and a range of other artifacts introduced during the fabrication process. As semiconductor features continue to shrink, molecular size introduces a second type of non-orthogonality into the fabrication process. This second type of non-orthogonality arises because the molecules used to form the features of semiconductors become increasingly large (in a relative sense) as the features become increasingly small. As a result, small features tend to exhibit a non-uniformity, or roughness, caused by the physical size of their constituent molecules. This is particularly true where organic photo-resists are used. Figure 3 shows a specific example where the use of relatively large molecules has resulted in line edge roughness.

Non-uniformity, or roughness of the type shown in Figure 3, changes the measurements recorded during the scatterometry process. This is problematic because the models used to predict the empirical scatterometry measurements are not designed in a way that predicts the type of measurements that are associated with rough edges or other non-uniformities. For many modeling techniques, this problem is exacerbated because they assume that the scattering sample is two-dimensional (as is the case for the sample of Figure 2).

For these reasons and others, a need exists for scatterometry techniques that are compatible with samples having rough or non-uniform edges. This need is particularly apparent for high density semiconductor wafers where feature sizes are small and particularly apparent where organic photo-resists are used.

SUMMARY OF THE INVENTION

The present invention provides a method for simulating line edge roughness within optical models of scatterometry samples. For typical applications, the sample is a semiconductor wafer and includes a scattering structure formed on one or more underlying layers. The lowermost of the underlying layers is commonly referred to as a substrate. The scatting structure is covered by an incident medium that is typically air but may be vacuum, gas, liquid, or solid (such as an overlaying layer or layers). In the most typical case, the scattering structure is a grating consisting of a periodic series of lines. By appropriate generalizations, other isolated or periodic features may also be modeled.

To model roughness, lines within the scattering structure are represented as combinations of three dimensional objects. A line, for example, can be modeled as a linear series of cylindrical mesas. The mesas, when spaced closely together (spacing is also described as pitch) resemble a line with an edge roughness that corresponds to the mesa size and pitch. By controlling mesa size and pitch, the roughness of many line edges may be effectively modeled. By including multiple series of mesas with differing sizes and pitches, arbitrary edge roughness can be modeled. This is somewhat analogous to combining different sine waves to construct arbitrary waveforms. It should also be noted that the number of mesas required may be reduced (for many types of edge roughness) by using elliptically shaped mesas, oriented in parallel with the line being modeled.

Another, related method for modeling edge roughness is to construct lines within the scattering structure to have variable cross-section. By changing the cross-section as a function of line position, arbitrary edge roughness may be modeled.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a diagram of a prior art optical metrology system.

Figure 2 is a perspective drawing of a typical scatterometry sample.

Figure 3 is a perspective drawing of a typical sample exhibiting line edge roughness.

Figures 4A through 4C are block diagrams showing a line with edge roughness modeled using three dimensional mesas.

Figure 5 is a perspective drawing of a sample exhibiting line edge roughness modeled using three dimensional mesas.

Figure 6 is a perspective drawing of a sample exhibiting line edge roughness modeled using three dimensional voids.

Figure 7A shows a first series of three dimensional objects.

Figure 7B shows a second series of three dimensional objects.

Figure 7C shows the series of Figure 7A superimposed on the series of Figure 7B.

Figure 7D shows a line edge modeled using the superimposition of Figure 7C.

Figure 8A though 8C show periodic functions of different frequencies.

Figure 8D shows a line edge modeled using the periodic functions of Figure 8A though 8C.

Figure 9A though 9C show periodic functions of different frequencies.

Figure 9D shows a line edge modeled using the periodic functions of Figure 9A though 9C.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention provides a method for simulating line edge roughness within optical models of scatterometry samples. For typical applications, the sample is a semiconductor wafer and includes a scattering structure formed on one or more underlying layers. The lowermost of the underlying layers is commonly referred to as a substrate. The scatting structure is covered by an incident medium that is typically air but may be vacuum, gas, liquid, or solid (such as an overlaying layer or layers). In the most typical case, the scattering structure is a grating consisting of a periodic series of lines. By appropriate generalizations, other isolated or periodic features may also be modeled.

To model roughness, edges within the scattering structure are represented as combinations of three dimensional objects. This is shown, for example, in Figure 4A where

a line is modeled using a series of cylindrical mesas. Each shape (mesa) has the same size and the series of shapes are aligned to define the edge of a line. The shapes are separated by a predetermined distance (pitch). As shown in Figure 4B, decreasing the linear separation between mesas (i.e., using more mesas per unit distance along the line) changes the texture of the line model. The overall size of the mesas (e.g., their diameter) may be varied to control line width and roughness.

In Figure 4C, the cylindrical mesas are replaced with elliptical mesas. The use of the elliptical cross section reduces the number of thee-dimensional objects required to model a given line. The use of ellipses also increases the types of roughness that may be modeled, since the dimensions of the ellipse (major axis, minor axis) are variable. A sample model using a combination of elliptical shaped mesas is shown in Figure 5.

It should be noted that circular and elliptical mesas are merely examples of three dimensional objects that may be used for the modeling method. Mesas may be defined to have any desired cross section (e.g., oval, triangular or square). Mesas may also be defined conically to have sloping sides. This can be used to model lines that have sloping sidewalls. It is also possible to model lines using combinations of voids. A specific example of this is shown in Figure 6 where a sample is shown to include a series of trenches. Each trench is modeled as a linear series of overlapping elliptically shaped holes. The samples of Figures 5 and 6 are, in this respect, conjugate halves, with the solids used to model the sample of Figure 5 replaced with voids for the sample of Figure 6. Holes can have any desired cross-section and maybe be constructed conically to represent lines with sloping sidewalls.

As shown in Figures 7A through 7D, it is possible to combine multiple series of three-dimensional shapes to model complex line edges. Figures 7A shows a first series of elliptical mesas (or holes) 702a and Figures 7B shows a second series of elliptical mesas (or holes) 702b. The mesas in series 702b are approximately twice as large as the mesas in series 702a. The mesas in series 702b are spaced with half the frequency of the mesas in series 702a (i.e., the pitch of series 702b is half of the pitch of series 702a). The two series start at the same position (i.e., the have the same relative phase).

Figure 7C shows a superposition of the two separate series 702. For this particular example, the series of smaller mesas (702a) has been aligned to coincide with the upper edge of the larger series (702b). The shape resulting from this superposition is shown in

Figure 7D. As shown, the upper edge of the resulting shape has an attenuated arc-like shape attributable to the addition of the smaller mesas. The lower edge of the resulting shape retains the arc-like nature of the series of larger mesas.

Figures 7A through 7D are intended to demonstrate that multiple series of three dimensional objects may be combined to represent arbitrary line edge roughness. Typically, where multiple series are used, each series will be different in some respect. The differences may be in terms of shape size (as is the case for series 702a and 702b) shape pitch (once again, demonstrated by series 702a and 702b) or shape offset (relative phase) or various combinations thereof which can be used to represent arbitrary line edge roughness. Combinations of this type may be used to define asymmetric lines of the type shown in Figure 7D where opposing edges have different roughness.

The preceding paragraphs describe the modeling of line edge roughness using collections of three dimensional solids and voids. A second technique models each line as a single three dimensional object. In terms of the coordinate system of Figure 5 and 6, each line is modeled to have a specific X-Z profile. Typically, this means that each line has a defined cross-section that is rectangular, trapezoidal or other symmetric or asymmetric shape. That shape is allowed to vary along the Y axis. This means that each line can increase or decrease in width or vary the shape of its profile as a function of position along the Y axis. In effect, each line can have a different cross-sectional shape for each Y location.

To define line profile as a function of position, one or more periodic functions may be used. In combination, the periodic function can be used to represent arbitrary line edge roughness. This is shown, for example, in Figures 8A through 8D. The first three of these figures (8a-8c) show different periodic functions for a single line edge. Figure 8D shows the combination of the three separate edge functions to generate an arbitrary edge. The combination of periodic shapes can be modified, amplified or reduced as a function of Z to further increase the type of edge roughness or non-uniformity that can be modeled. In general, it is possible to model any desired edge profile as a Fourier decomposition of periodic functions. As an example, Figure 9A shows a sine function of a given frequency and amplitude. Figures 9B and 9C show odd harmonics of the sine function of Figure 9A. The combination of these three functions results in the square wave line edge of Figure 9D.

Fourier decomposition may be used to model edge profiles that have a repeating pattern (as in Figure 9D) as well as non-repeating edge profiles.

Scattering structure models may be constructed using any of the techniques described in the preceding sections. Once constructed, the models may be evaluated using any appropriate three-dimensional approach. Two particularly appropriate approaches are described in the co-pending U.S. Patent Application Serial Nos. 10/212,385, and 10/345,814. Those disclosures are incorporated in this document by reference. See also: "Contact hole inspection by real-time optical CD metrology," Opsal, et al. SPIE Microlithography 2003, pages 5038-63 and "Optical digital profilometry applications on contact holes," Bischoff et al, Metrology, Inspection, and Process Control for Microlithography XVII, Proc. of SPIE Vol. 5038, pp. 1080 – 1088, 2003, both incorporated herein by reference.

In use, a sample is optically inspected using any of the conventional optical inspection techniques discussed above and represented generically by Figure 1. In the preferred embodiment, a spectroscopic reflectometer or spectroscopic ellipsometer (or a combination of both) is used to generate measurement signals as a function of wavelength. These signals are compared to theoretical signals which are generated based on the model of the subject invention. The theoretical signals could be generated in the form of sets of data in a database representing a range of different sample parameters. Alternatively, the parameters of the model can be iteratively modified in order to minimize the differences between the measured signals and the theoretical data.